SESSION VI

ALUMINUM FOIL EXPANDABLE STRUCTURES

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Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **1965**	2. REPORT TYPE	3. DATES COVERED **00-00-1965 to 00-00-1965**
4. TITLE AND SUBTITLE **Aluminum Foil Expandable Structures**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **AVCO Corporation,Research and Advanced Development Division,Wilmington,MA,01887**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**		**32**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

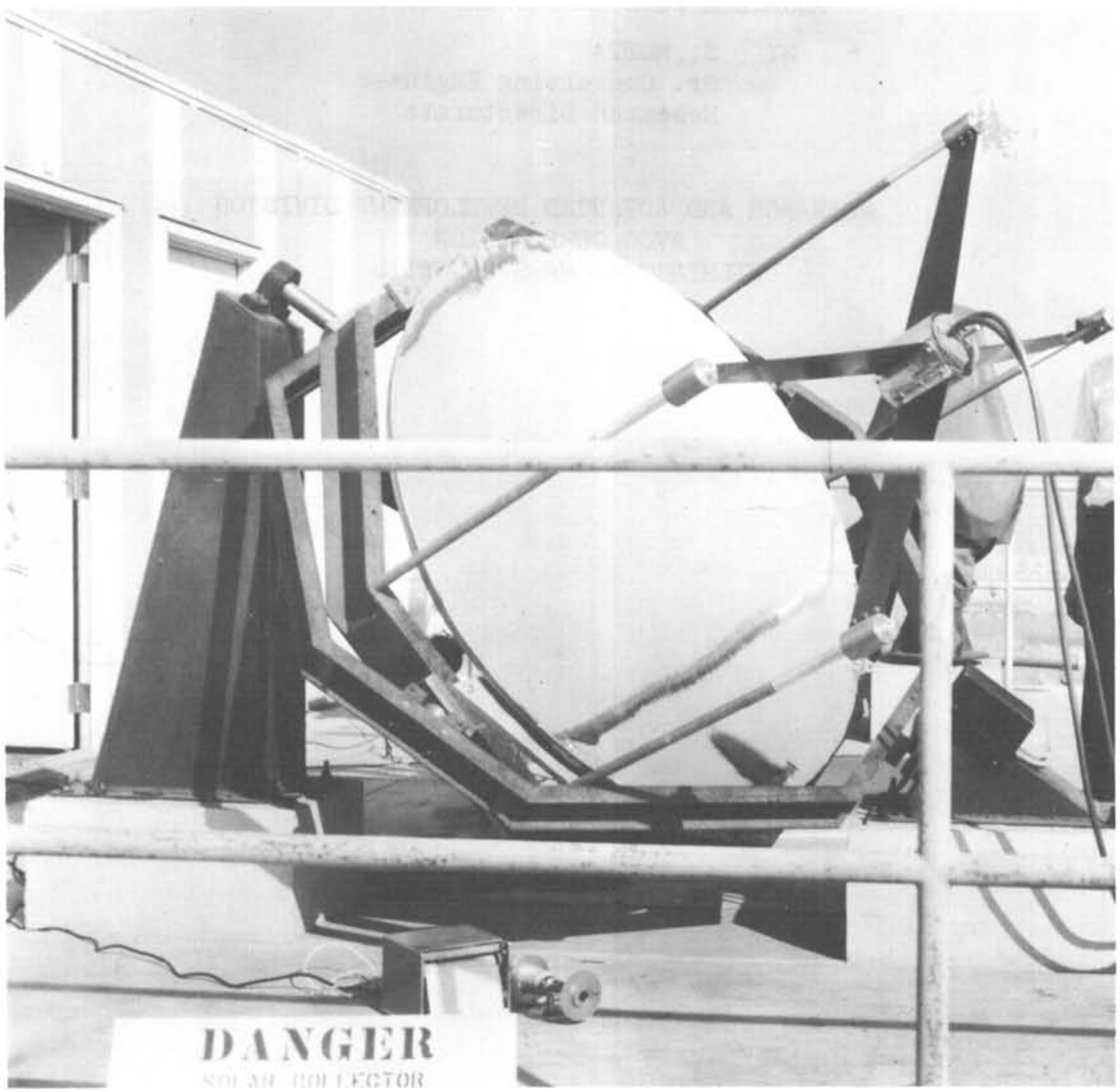


Figure 9 Test Set-up for Determining Calorimetric Efficiency

ALUMINUM FOIL EXPANDABLE STRUCTURE

INTRODUCTION

The work presented in this paper is the result of an investigation conducted by the Research Directorate of Avco RAD, largely company sponsored, to determine the feasibility of using aluminum foil to fabricate expandable space structures.

The choice of a metallic foil, over the more pliable plastic counterpart, was dictated by the two goals we set out to reach:

(1) Automatic rigidization of our deployed shapes

(2) The highest possible reliability index of our structures to survive space environment.

A survey of the field indicated that most of today's expandable structures fall into one of the following categories: (a) pressure dependent structures, (b) structures achieving rigidization through the medium of additives such as resins, permanently bonded to the expandable material, and finally (c) foamed in place double wall structures. Each category does justice to a particular set of structural requirements and, I am sure, is not meant to be offered as an optimum solution to all inflatable structural problem.

Our structure is not pressure dependent, does not use resins or foam for its rigidization, and therefore, does not fall in any of the aforementioned categories nor does it necessarily attempt to solve the same type of problems.

Our entire approach to the general problem of inflatables stems from the very basic fact that if you stretch a piece of aluminum foil so as to induce a membrane stress of 5,000 to 6,000 psi, depending on its thickness, you have caused the foil to reach a state of permanent set, allowing it to retain its inflated shape even after complete depressurization.

Briefly stated, we set out to achieve rigidity as a by-product of controlled stretching, and thereby substantiate our first goal of automatic rigidization.

It was reasoned that if this state of metallic "rigor mortis" so to speak, could be achieved by using dead soft aluminum foil as bought from the producer, without any special treatment, we would be well on our way to substantiating our second goal, i.e. a high reliability index. The rest of this paper will offer documentary proof of the feasibility of the concept. Before getting into the more technical aspects of the problem, however, and in order to provide a ready visual reference to some of the facts and figures to follow, I should first like to show a movie of the erection of a corner reflector which was our first piece of hardware following a thorough study of the physical properties of our medium: 99% pure dead soft aluminum foil.

It consists of six arms deploying in the x,y,z directions from a central pressure source located at the origin of the axis. The first frames show a two foot model with triangular mylar sails going through the expansion three times. This is followed by the erection of one of the six arms full size. It is a column 16 ft. high, 6 inch diameter, $\frac{1}{2}$ mil thick. (3 minutes of movie follows).

The fabrication of this corner reflector was, of course, preceded by a thorough study of the foil itself. Several foils were screened for mechanical and chemical properties before it was decided to work with aluminum foil 1145 H2E4. This is Alcoa's designation for a foil with a nominal purity of 99.5% aluminum. Although this foil is usually annealed before final inspection, Alcoa chose the term H2E4 to denote the residual temper due to cold work generated by the rollers. Several thicknesses of foil were analyzed for chemical composition. The following table shows the results of our chemical study.

TABLE I

Nominal Thickness of Sheet (inches)	Alcoa Lot No.	Element %							
		Fe	Cu	Ti	Mn	Mg	Zn	Si	Al
0.0005	966-874	0.1	0.05	0.01	0.01	0.01	ND*	0.01	99.72
0.0010	966-878	0.1	0.05	0.01	0.01	0.01	ND*	0.01	99.72
0.0015	966-875	0.1	0.05	0.01	0.02	0.01	ND*	0.01	99.71

* not detected

Variations in thickness were another problem. Alcoa reports the commercial tolerance of thickness control is $\pm$ 10% of nominal. This appears to be generally true although very accurate measurements with a Van Kewren light wave micrometer revealed deviations as great as 14%.

TABLE II

VARIATION OF FOIL GAGE WITHIN A GIVEN LOT

Nominal Thickness (inches)	No. of Observations	Range of True Thickness (inches)	Max. Deviation From Nominal (%) Thickness
0.0015	48	0.0015 - 0.00160	+6.6
0.001	42	0.00109 - 0.00114	+14
0.0005	51	0.00052 - 0.00057	+14

Aluminum foil is likely to contain tiny perforations commonly referred to as "pin holes" which seem to be the inevitable result of rolling metal to very thin gages. The following table summarizes the results of microscopic examination conducted by Alcoa, where 100 sheets were examined for each gauge.

TABLE III

TYPICAL VARIATION OF PINHOLES WITH GAGE

Nominal Thickness of Foil (inches)	Number of Sheets With Pinholes	Number of Sheets with no Pinholes
0.00035	100	none
0.0005	100	none
0.0007	15	85
0.001	8	92

Exhaustive stress-strain studies were made. The specimens measured approximately 6" in length and 0.50" in width, the edges being parallel throughout the length. Because of the thinness of the foil accurate determination of cross sectional area was critical. Hence, all measurements were made by Avco's measurements section. The width was measured to ± 0.001 by a "Sip" machine and the thickness ± 0.000010" by a Van Keuren light wave micrometer. Tables IV to VII show the results.

Figure 1, page 7, shows typical stress strain curves for the range of thicknesses used in our work. Both yield and ultimate stresses increase with the thickness of the foil. This effect is believed to be the result of nicks, severed edges, non uniformity and the wrinkles which cold work the material all of which are most likely to occur in specimens of smaller gauges.

Figure 2 plots this effect, as well as the percentage elongation for the various thicknesses. The results reported for elongation were determined by fitting the fractured specimens together and measuring the distance between gauge marks.

Armed with this information, we started fabricating our column test samples. Seam bonding of the edges, required for the fabrication of a tubular member, was one of

TABLE IV

TYPICAL STRESS-STRAIN PROPERTIES OF 1145-H2E4 ALUMINUM FOIL, 0.005 IN. GAGE

With Respect To Rolling Direction	Yield Stress .2% Offset PSI	Ultimate Tensile Stress, PSI	Young's Modulus E x 10 10^{-6} PSI	Elongation (%)
	4260 4140 3900 3940	6240 6450 5840 6090	10.0 10.1 10.0 9.9	0.9 1.1 1.0 1.4
	4060 170	6155 260	10.0 0.08	1.1 0.22
	3990 4180 4080 4040	5800 6080 5950 5510	10.0 9.8 9.9 10.0	1.1 1.1 1.2 0.86
	4073 80	5835 250	10.0 0.15	1.1 0.14

TABLE V

TYPICAL STRESS-STRAIN PROPERTIES OF 1145-H2E4 ALUMINUM FOIL, 0.01 IN. GAGE

With Respect To Rolling Direction	Yield Stress .2% Offset PSI	Ultimate Tensile Stress, PSI	Young's Modulus E x 10 10^{-6} PSI	Elongation (%)
	3760 4310 4120 4200 3980 4030	6890 6820 6980 6800 6390 6280	9.9 9.9 10.1 10.2 10.0	2.3 2.3 2.3 2.3 1.6 1.6
	4067 190	6693 290	10.0 0.13	2.07 0.36
	4250 3920 3900 3760 4170 4090 4030	6370 6240 6410 5990 6570 6480 6280	9.6 10.1 10.4 9.9 9.8	1.6 2.3 2.0 1.6 1.6 2.0 1.6
	4017 170	6334 190	10.0 0.31	1.81 0.29

TABLE VI

TYPICAL STRESS-STRAIN PROPERTIES OF 1145-H2E4 ALUMINUM FOIL, 0.0015 IN. GAGE

With Respect To Rolling Direction	Yield Stress .2% Offset PSI	Ultimate Tensile Stress, PSI	Young's Modulus E x 10 10^{-6} PSI	Elongation (%)
	3970 4070 4040 4560 4190	7930 8350 8530 8040 8140	9.6 10.2 9.9 9.9 10.0	3.1 3.9 4.7 3.3 4.7
	4166 230	8198 240	9.9 0.22	3.94 0.76
	4070 4100 3910 4070 4120	7730 7810 7460 7440 7570	9.4 10.1 10.0 9.8 10.2	4.5 4.7 3.9 3.9 3.9
	4054 80	7602 160	9.9 0.32	4.18 0.39

= sample arithmetic mean

= standard deviation

Identical tests for t = 0.002 and t = 0.005 yielded the following results:

TABLE VII

RAD FGT TESTING MACHINE

Spec. No.	Nominal Thickness (inches)	Ultimate Stress (psi)	Yield Stress (0.2% offset) (psi)	Elongation %	Young's Modulus E x 10^6 (psi)
2-1	0.002	8290	4370	6.3	10.0
2-3	0.002	8590	4570	6.2	10.1
5-1	0.005	12000	5360	7.8	10.1
5-3	0.005	11900	5700	12.5	--

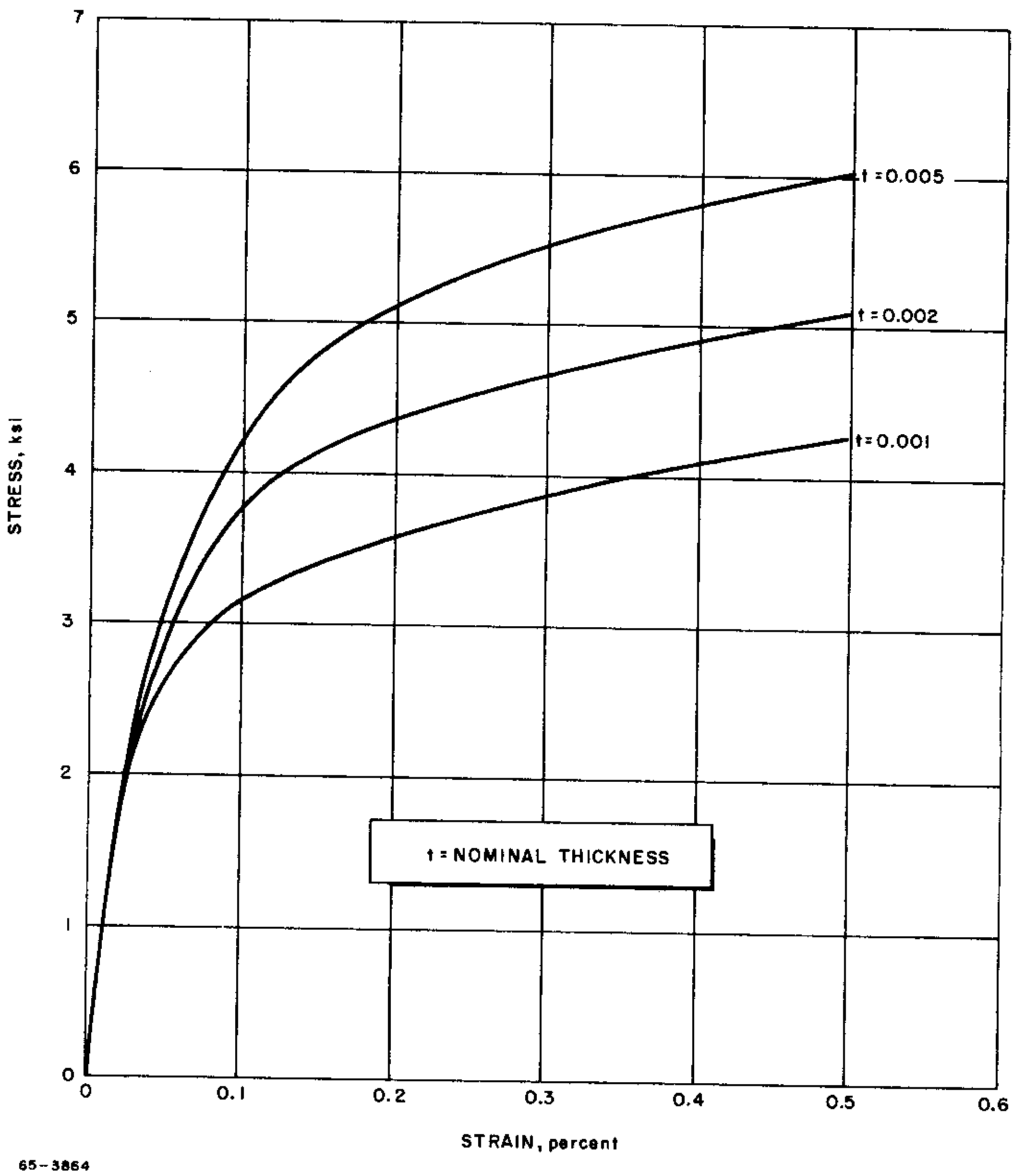


FIGURE 1 TYPICAL STRESS-STRAIN CURVES

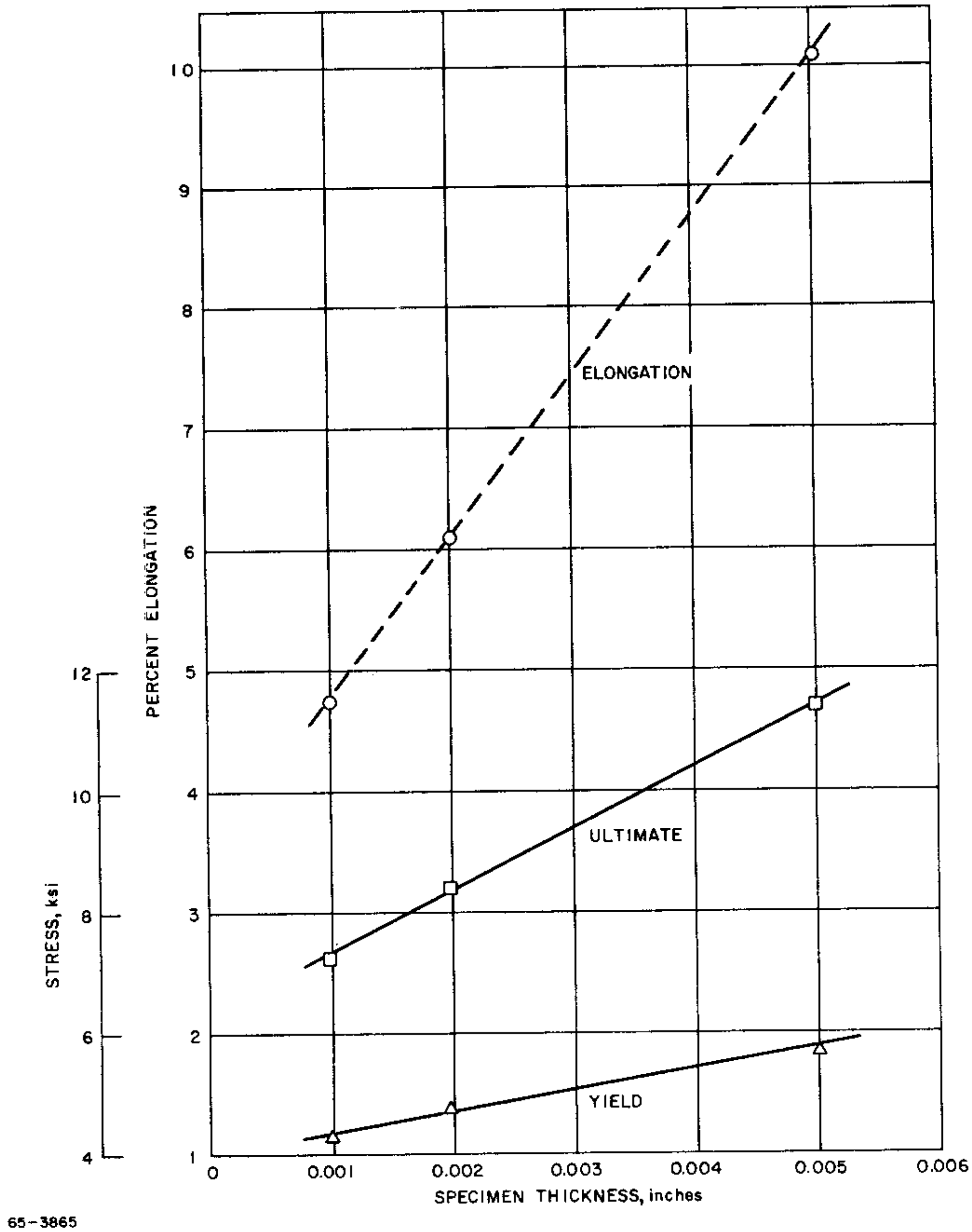


FIGURE 2 VARIATION OF ULTIMATE STRESS, YIELD STRESS AND ELONGATION vs. THICKNESS

the first hurdles. The modern advances in electron beam welding have made the edge welding of two aluminum foils a matter of routine. An adapter kit was designed for installation on a Hamilton Standard electron beam welder, which would allow the wrapping of two identical aluminum foil ribbons on a round reel. The free ends of the ribbon are made to pass through two copper chill plates and on to the driver reel. The electron gun aims directly at the free edges of the ribbons and starts welding as soon as the chill plates have locked on to the foils. The operation is repeated until the full length of one edge of the foil is welded. To weld the other edge, you reverse your reels and proceed as before. This is a recent development and was not available at the time we were ready to run the tests.

For the purpose of our tests, however, where life expectancy was not the important problem, ordinary cellophane tape was found adequate to carry the hoop stresses caused by internal pressure. Figure 3 shows a typical test setup for the tubes thus fabricated. A gravity loading system was used in the test, allowing a positive determination of collapse of the tube. Each tube was inflated to a pressure corresponding to a calculated hoop stress equal to its yield. The pressure was measured with a manometer connected to the air supply hose. By using a plump bob for guiding and shims under the base, the tube was aligned vertically. Loading was accomplished by slowly adding lead shot to the receptacle until collapse occurred; at this time, the funnel took up its initial slack and became suspended by the ropes as shown. This, of course, was done to prevent scattering of the lead shots. Failure under column load occurred by local crippling at a section where some imperfections existed or one near the fixed end. Table VIIIshows the size of the tube tested and the crippling stresses at failure. The results are plotted on Figure 4.
The r/t ratio is plotted against the ratio of the crippling stress versus the yield allowable (σ_C / σ_Y). Curves were drawn to fit the test points. There is an obvious

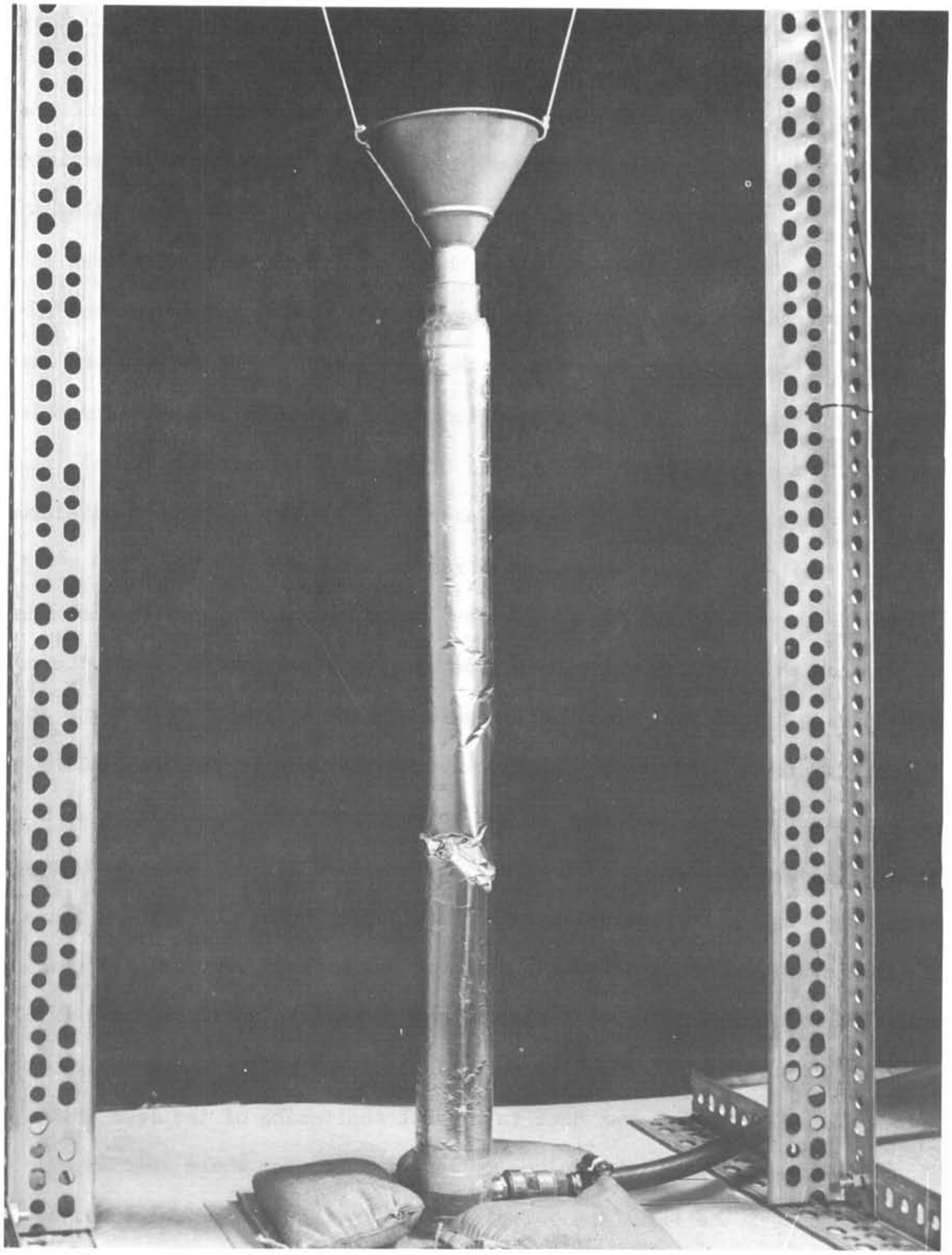


FIGURE 3 TYPICAL TEST SETUP

TABLE VIII

TEST DATA--ALUMINUM TUBES

Tube Size	Test 1		
D x t	p Inflation Pressure	Collapsing P_c Load	Collapsing c Stress
1.5 x 0.0015	14.0 psi	5.03 lbs.	711 psi
2.0 x 0.0015	10.5	6.55	695
3.0 x 0.0015	7.0	6.59	467
4.0 x 0.0015	5.2	11.5	610
5.0 x 0.0015	4.2	8.19	347
6.0 x 0.0015	3.5	9.12	322
12.0 x 0.0015	1.75	11.46	203
2.0 x 0.0010	7.0	2.69	428
3.0 x 0.0010	4.6	5.10	541
6.0 x 0.0010	2.3	7.54	400
12.0 x 0.0010	1.17	5.08	134
2.0 x 0.0005	3.5	0.94	299
3.0 x 0.0005	2.3	1.06	225
6.0 x 0.0005	1.17	1.29	137
12.0 x 0.0005	0.58	---	---

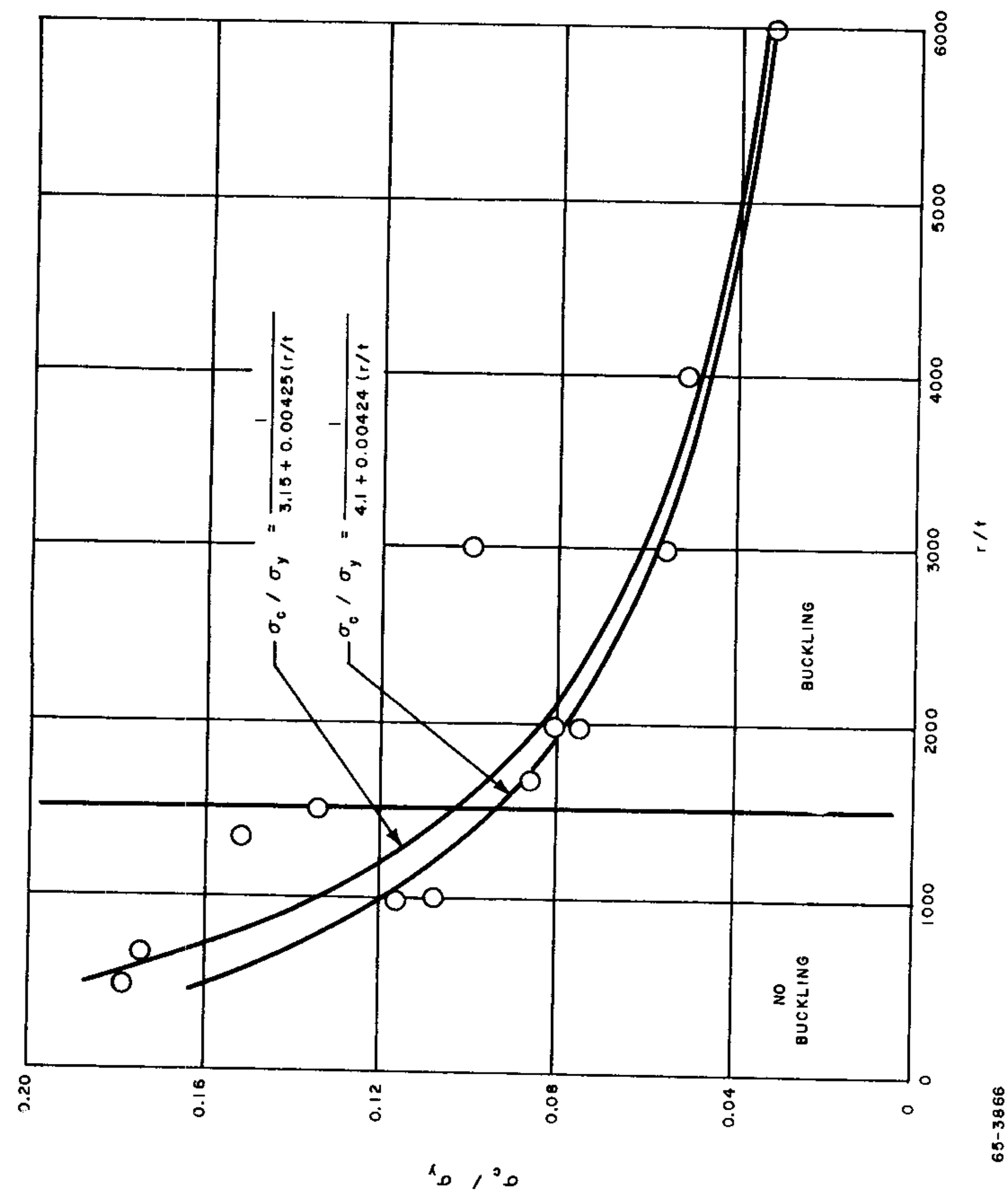


FIGURE 4 TEST RESULTS AND EMPIRICAL CURVES

trend of decreasing stress with increasing and the nature of the trend suggests an expression of the following type to fit the data

$$\frac{\sigma_c}{\sigma_y} = \frac{1}{a + b\left(\frac{r}{t}\right)}$$

The numerical values for a and b that best suited the curves are given in Figure 4. As previously stated, the corner reflector was our first piece of tangible hardware.

This was followed by a series of conceptual studies in connection with several proposal programs. Some experimental work was done on isolated ideas but none of them reached hardware stage. As all creative designers well realize, many details require imagination, intuition, skill and some tests to assess their true value. Nevertheless, a few of these conceptual studies are presented here with the full conviction borne out of our experience that they are plausible and in many cases state-of-the-art.

1. Structures Suited for Solar Reflectors and Circular Antennas

A series of 36 gores are seam-bonded to each other over a spherical master mandrel. The outer edges of the gores are draped over a toroid of circular cross section and the inner edges are tucked in between two rigid plates forming the base of a central pylon. The entire assembly is covered by a hemispherical balloon to entrap the gas pressure that will be used to stretch the gores beyond their yield point. The toroid will be inflated first by a self-contained gas generator. This will be followed by the inflation of the balloon. The rigidity of the individual gores is enhanced by treating them with a film of glycerine on the non-reflecting face which will boil off in the presence of vacuum, leaving a hard crust. The central pylon can be used to support a thermionic converter for the generation of electricity or a reflecting horn in the case of a space foldable antenna. Figure 5 shows a schematic of the concept and Figure 6 shows a 6' foot collector with a partial vacuum maintained on the underside. The gores are aluminum foil, 0.001" thick.

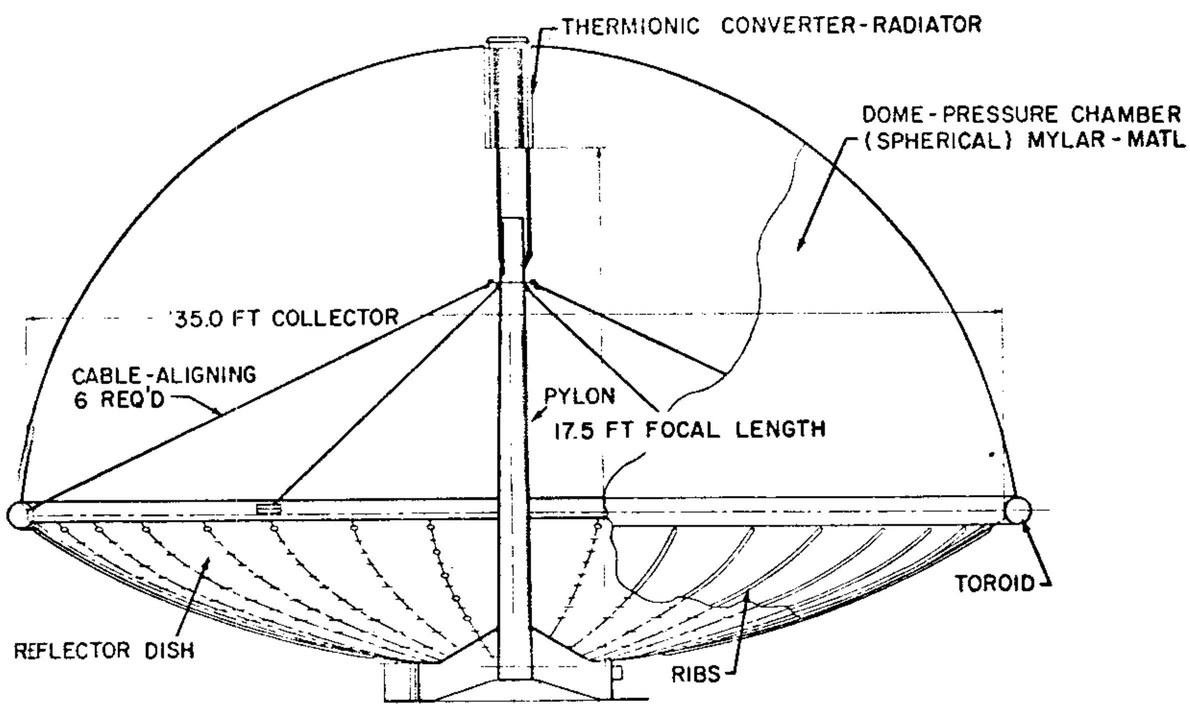


FIGURE 5 POWER PLANT SYSTEM WITH EXPANDED TUBE-SUPPORTED COLLECTOR

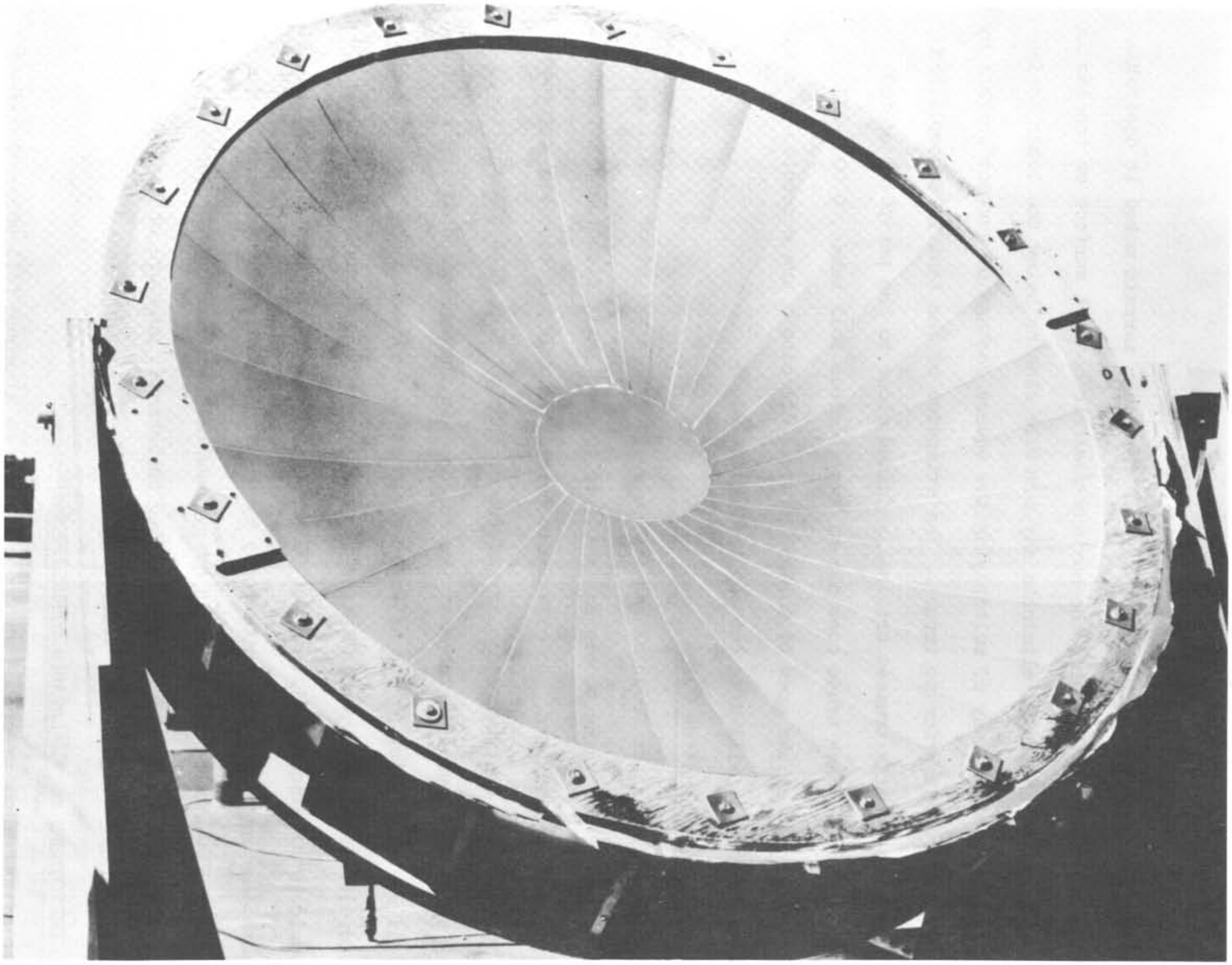


FIGURE 6 SIX-FOOT SOLAR REFLECTOR UNDER NEGATIVE PRESSURE
P5677B

2. Soft Lunar Landing Problem

The uncertainty surrounding the nature of the lunar terrain makes it desirable to originate a system of obtaining the maximum possible contact surface on the landin vehicle to retard or hopefully eliminate any possible sinking below the lunar surface Figure 7 shows a simple way of multiplying the square footage of contact surface by stretching a mylar tent prior to impact. The extension of the tent is accomplished by ten expandable tubular trusses originally folded close to the periphery of the vehicular structure. Each truss consists of two aluminum foil tubes, 0.003 wall thickness, connected at the apex by a rigid elbow. All elbows are connected by a wire which, upon expansion, will drag out the tent material.

3. Anti-Contamination Pylon

All S.N.A.P. Reactor Programs required a considerable weight of shielding material (250 lbs. according to one estimate) to protect their electronic assemblies from radiation contamination. An expandable pylon with foldable bays was designed. Each bay was defined by two triangular end frames made of flat fiberglass plate, separated by three expandable tubes at the apices. In the stowed condition the tubes were folded ribbons, allowing the triangular plates to be stacked up close to each other accordion fashion. Upon inflation the electronic tray, mounted on the outer end frame, would be displaced a distance of 90' from the source of contamination. See Figure 8

Many other applications limited only by the imagination of the designer can be conceived. The resulting structure in every case has the important property of retaining its deployed shape, without relying on internal pressure or hard to control chemical reactions.

ASSISTED DEPLOYMENT OF INFLATABLE STRUCTURES

All of the ideas presented so far are based on aluminum foil whose thickness varies from 0.0005 to 0.003.

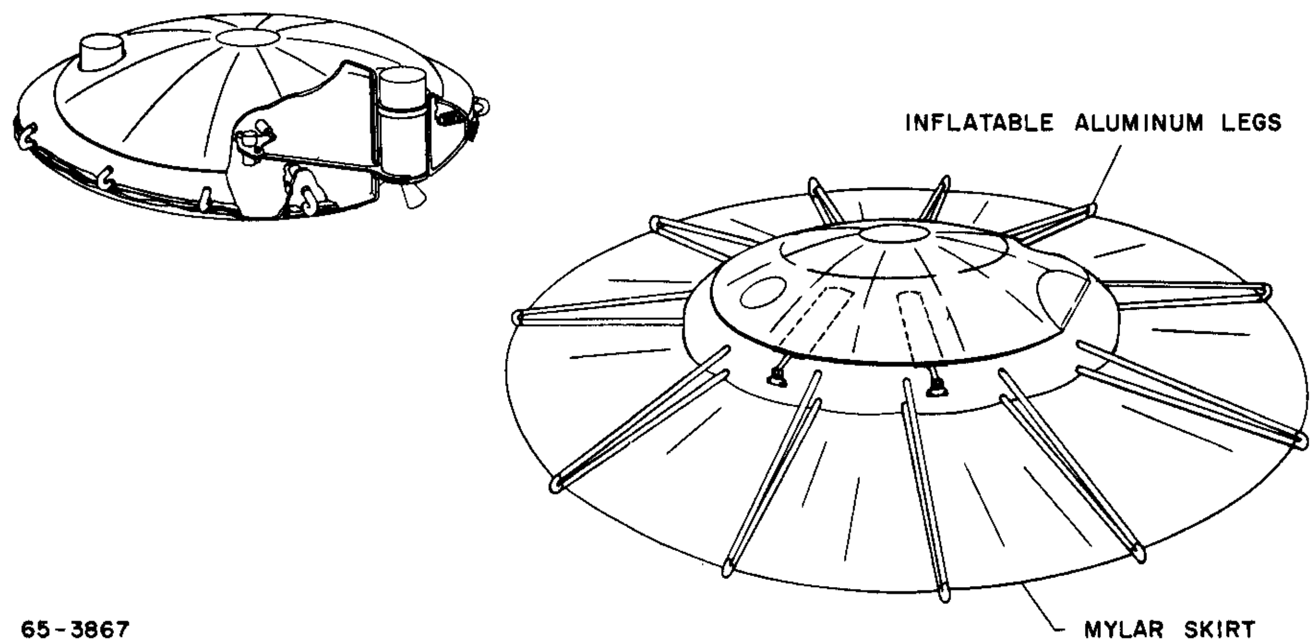


FIGURE 7 WEBBED MAT--HOVERING AND LANDING CONFIGURATION

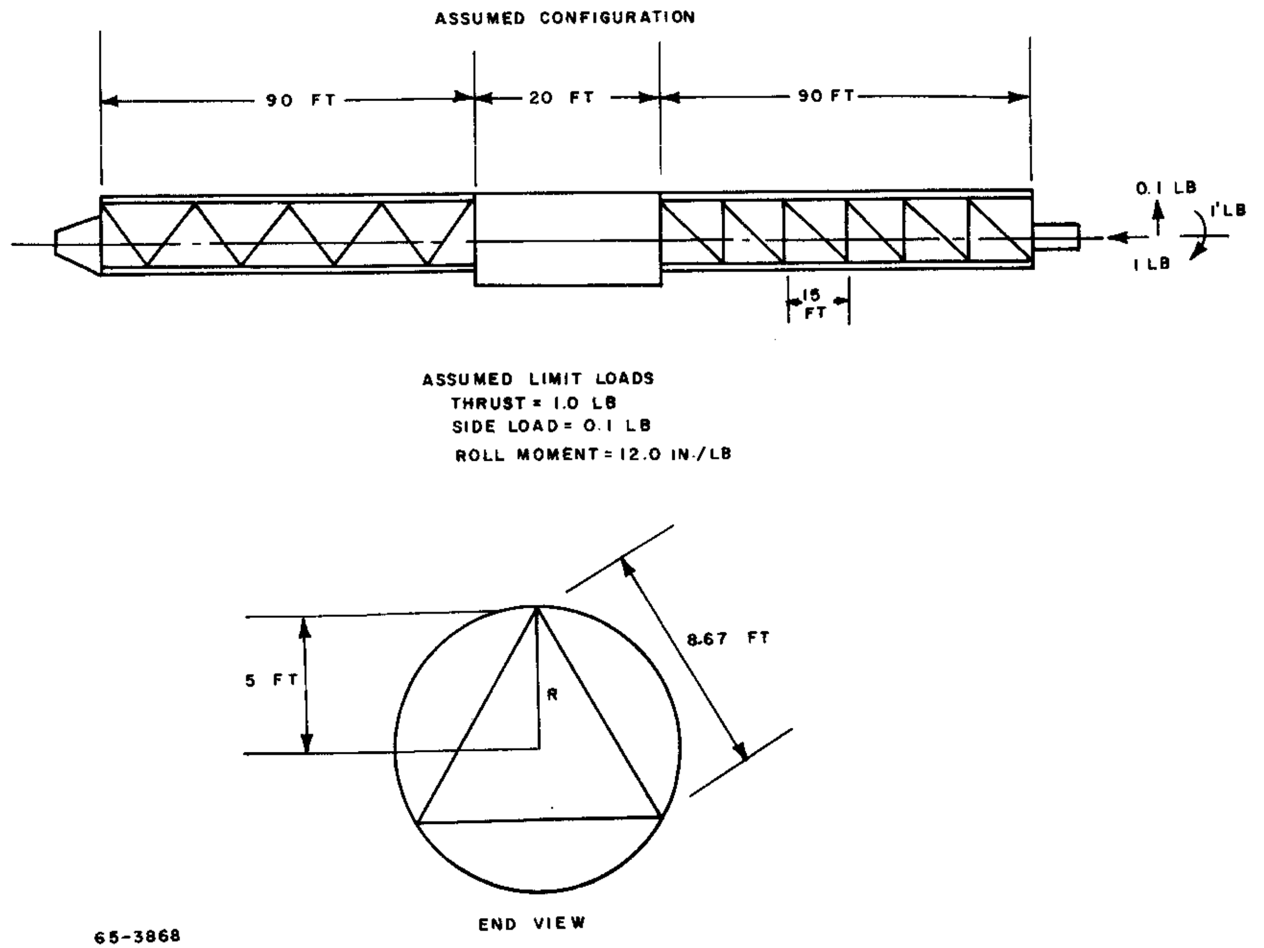


FIGURE 8 EXPANDABLE PYLON

The hardware we will present at this point deals with thicknesses from 0.003 to 0.006. The basic operational difference between these two types of structures is to be found in the method of deployment.

The thinner structures will pass from their stowed configuration to their final geometry by means of internal pressure only, as shown by the movie. The thicker structures, when similarly pressurized, never quite make it. They need an assist. A tube 1" O.D., for example, and 0.005" wall thickness will rigidize into a perfect tube when inflated from a straight flat ribbon. However, if it is folded first, carefully avoiding any sharp corners, and then pressurized from its folded geometry, it will not straighten out into an acceptable strut. Re-annealing after folding offers a partial remedy, but results are not structurally acceptable. We had reached an impasse. The question was, Shall we see what results we get by providing the assistance needed? Is it worth this new complication? or, Should we forget about it? It was decided to go ahead with the experiment. An external force was used to pick up the folded structure at some convenient point and hold it up in its stretched shape long enough to pressurize the tubes. The force required is minimal. It could be a buoyancy force, such as a balloon or a float, or it could be a micro-thruster for space work. Its only function is to allow pressurization to occur at or near final configuration.

The first legitimate basis we had to run this experiment was in connection with the Navy ASW Program. I am not at liberty to go into details for security reasons. The only object in mentioning it is to explain why in the next movie you will see the forming of a tube underwater by utilizing the buoyancy force of a float. Obviously, the same objective can be achieved in air or space. ($2\frac{1}{2}$ minutes of movie follow)

The resulting tube was cut in various lengths to cover a slenderness ratio from 20 to 180, and the specimens thus obtained were subjected to a typical column test (Ref. pg. 20 Figure 9).

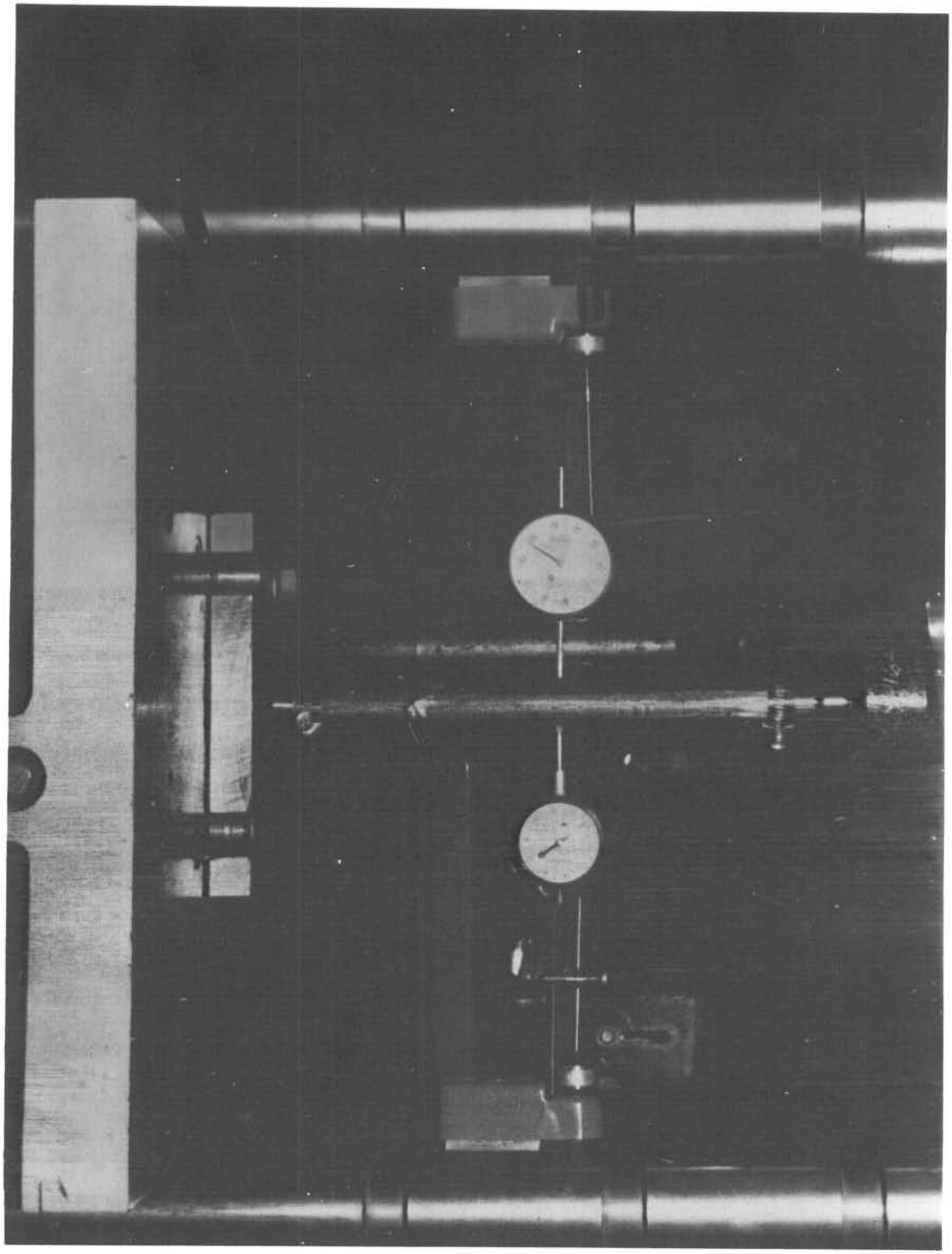


FIGURE 9 TYPICAL COLUMN TEST

The solid line on Figure 10 shows a plot of test points, and the dotted line shows results calculated on the basis of a simple Euler type formula.

$$P_{column} = \frac{\pi^2 EI}{L^2} \quad \text{lbs.}$$

The agreement is very satisfactory. The structural behavior of these tubes has proven to be very predictable. It was demonstrated again in the construction and testing of the equilateral tripod shown on Page 23 . The following movie shows the erection and inflation of this space truss in water. (3 minutes of movie)

After draining the water out of the tubes, this truss was tested for the loading condition shown in Figure 12 to assess its strength against a vertical load. Figure 13 plots load increments versus deflections to a failure load of 147 lbs. The weight of the tubes and fitting is approximately ½ lb., exclusive of the anchoring device.

Another problem whose solution eluded us for a long time, is the fabrication of a toroid of circular cross-section starting from a flat ribbon. The basic problem here is that the circumferential length of an element of a toroid is proportional to its distance from the center line of symmetry. The outer fibers are obviously longer than the inner ones. Starting with a ribbon made up of two flat strips, seam welded at the long sides, it was necessary to find a way of stretching the outer ribbon without disturbing the inner one. Also, the amount of stretching for each fiber had to be proportional to that fiber's distance from the center of the toroid. The answer is illustrated by Figure 14.

The ribbon is draped over the periphery of a solid wooden mold and tightened against it with a nominal tension load. Upon introducing pressure the ribbon is forced to expand outwardly, thus inducing a variable tension stress on all fibers of the cross section: zero at the inner fiber and 6000 psi. approximately at the outermost one.

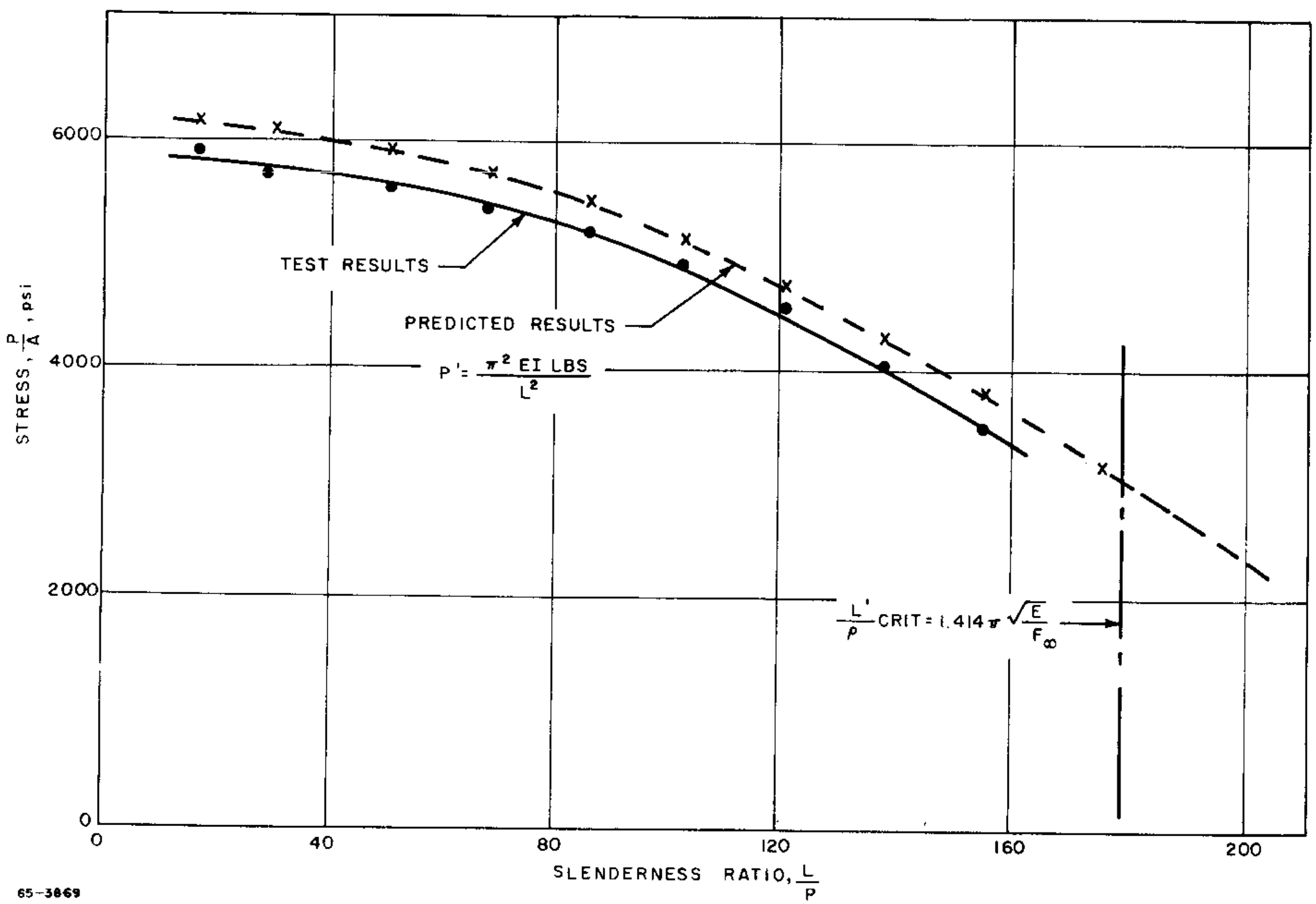


FIGURE 10 TEST RESULTS: SLENDER RATIO VERSUS CRITICAL STRESS AT FAILURE

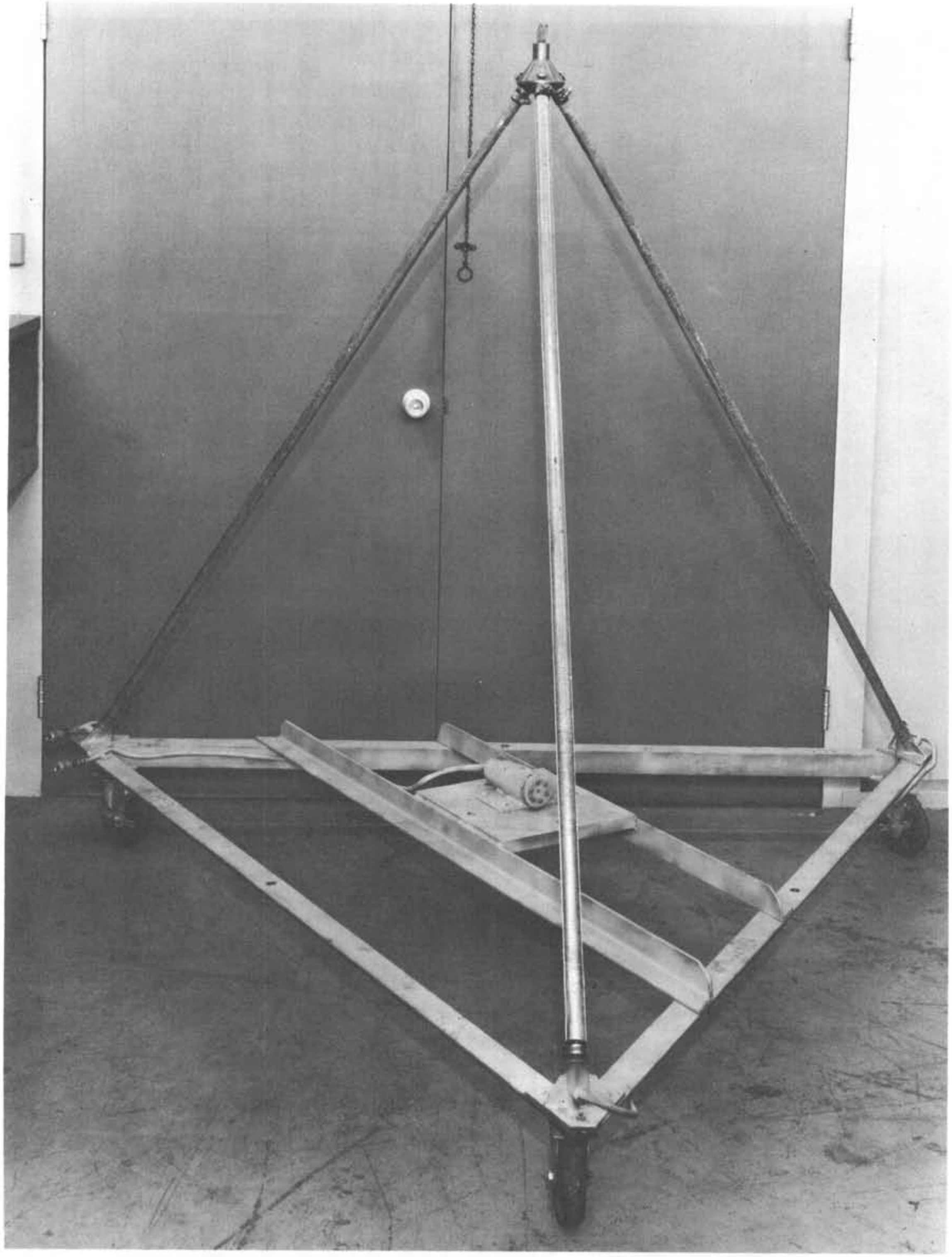


FIGURE 11 EQUILATERAL TRIPOD

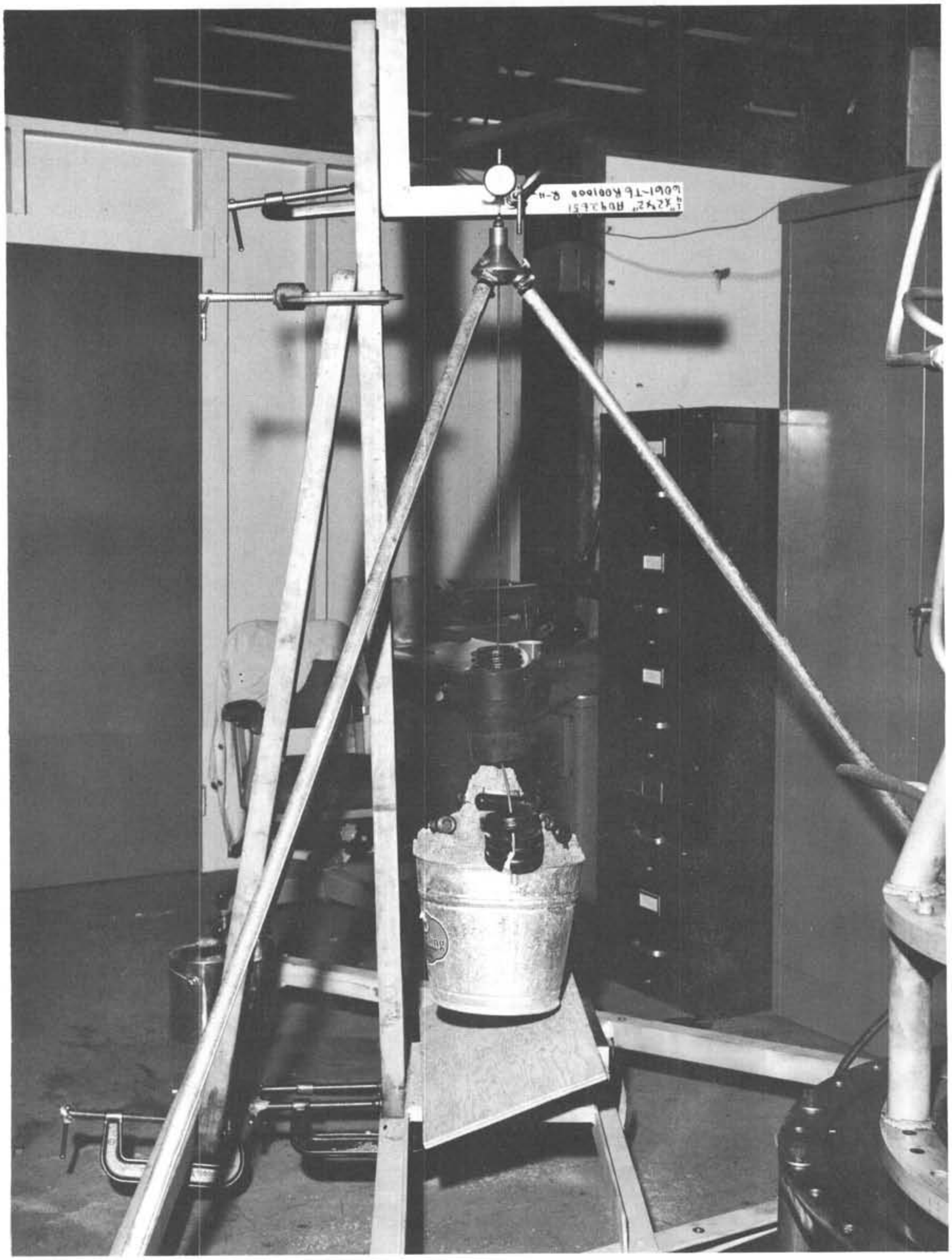


FIGURE 12 TESTING JIG FOR SYMMETRICAL VERTICAL LOADING

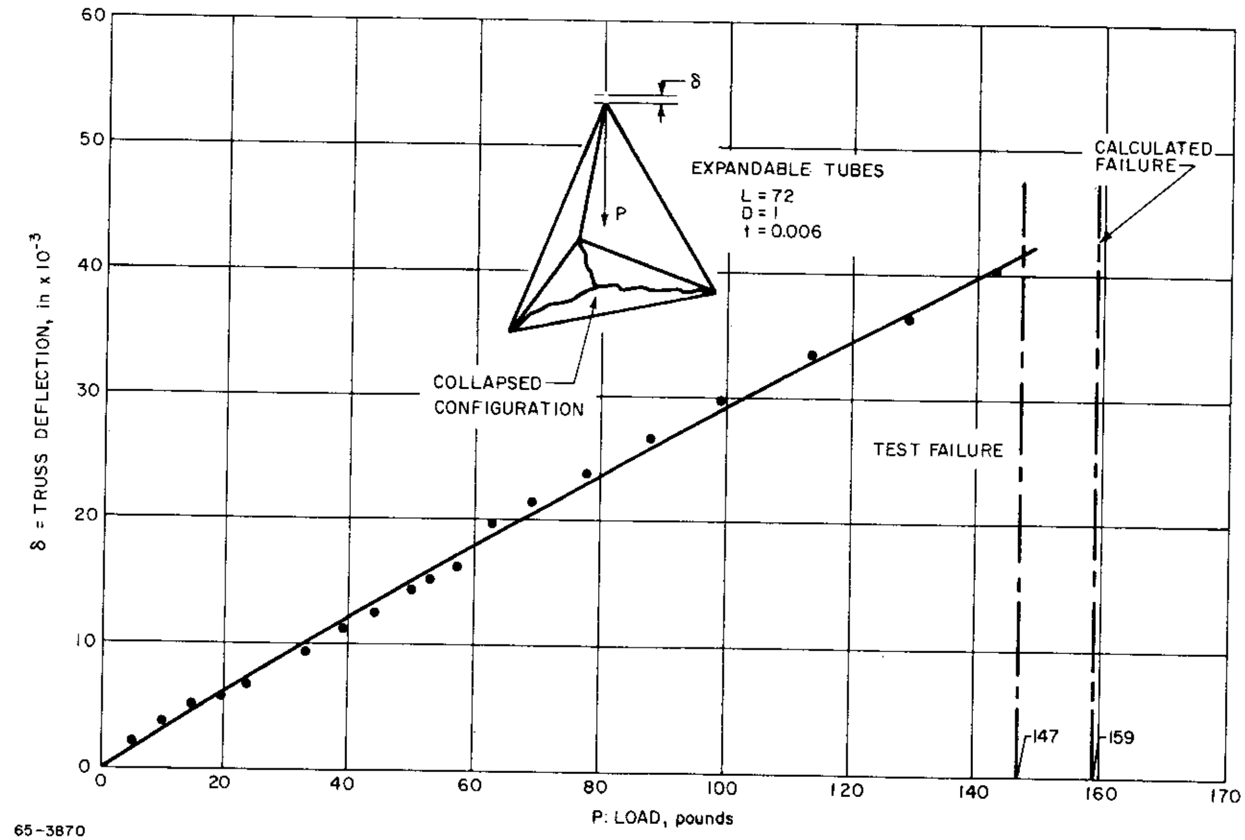


FIGURE 13 DEFLECTION OF TRUSS VERSUS VERTICAL LOADING

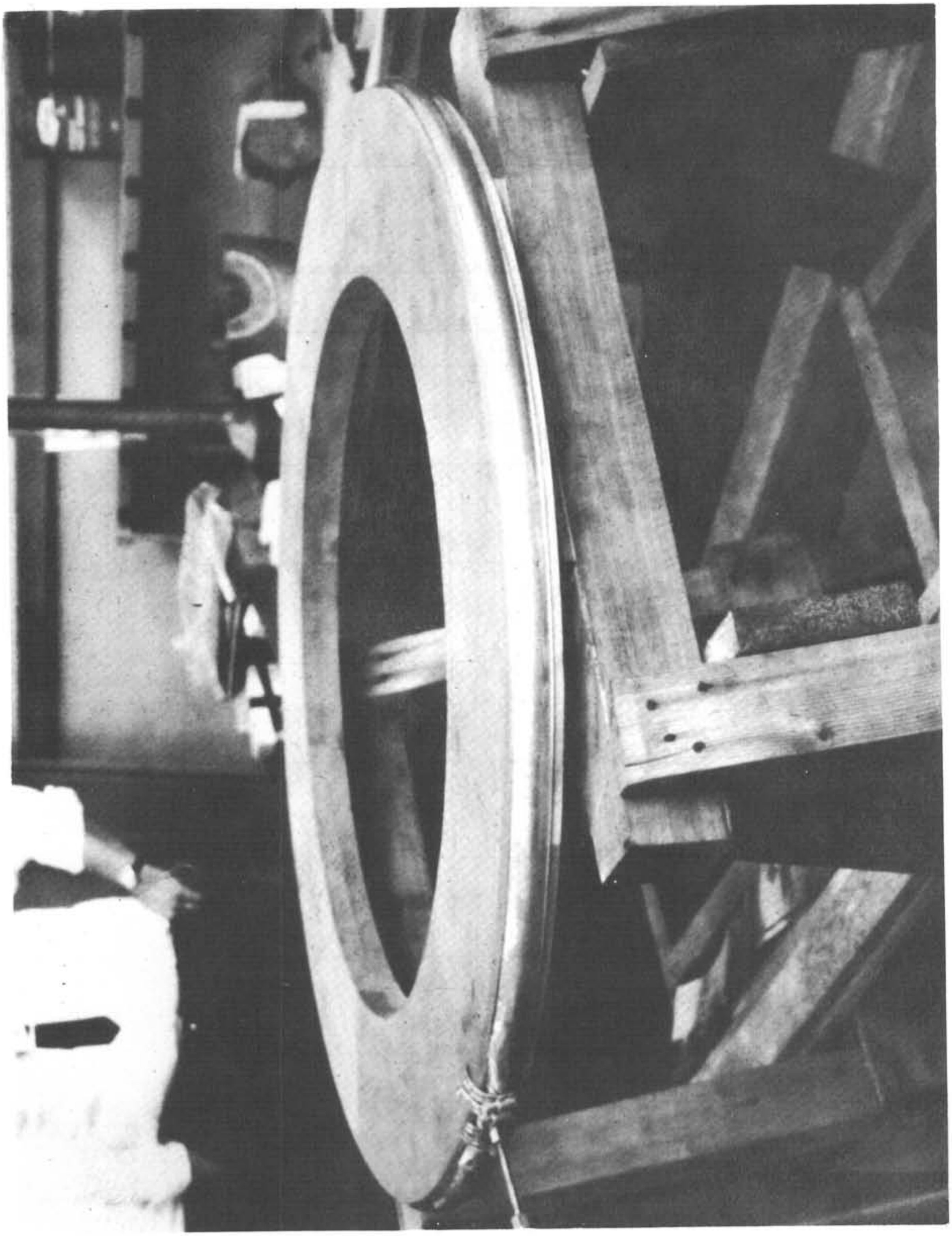


FIGURE 14 FABRICATION METHOD FOR A CIRCULAR TORUS

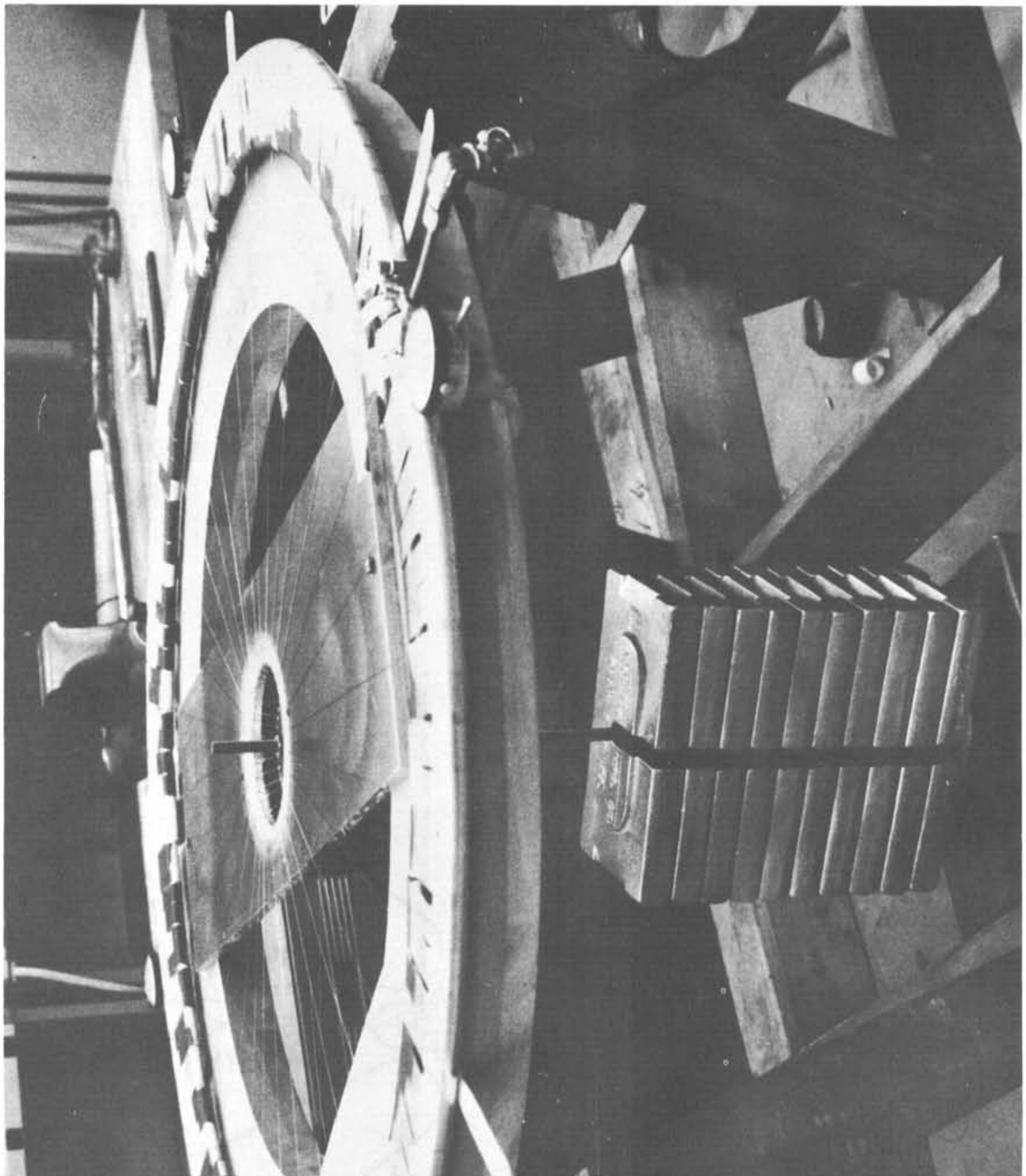


FIGURE 15 TORUS TEST SETUP

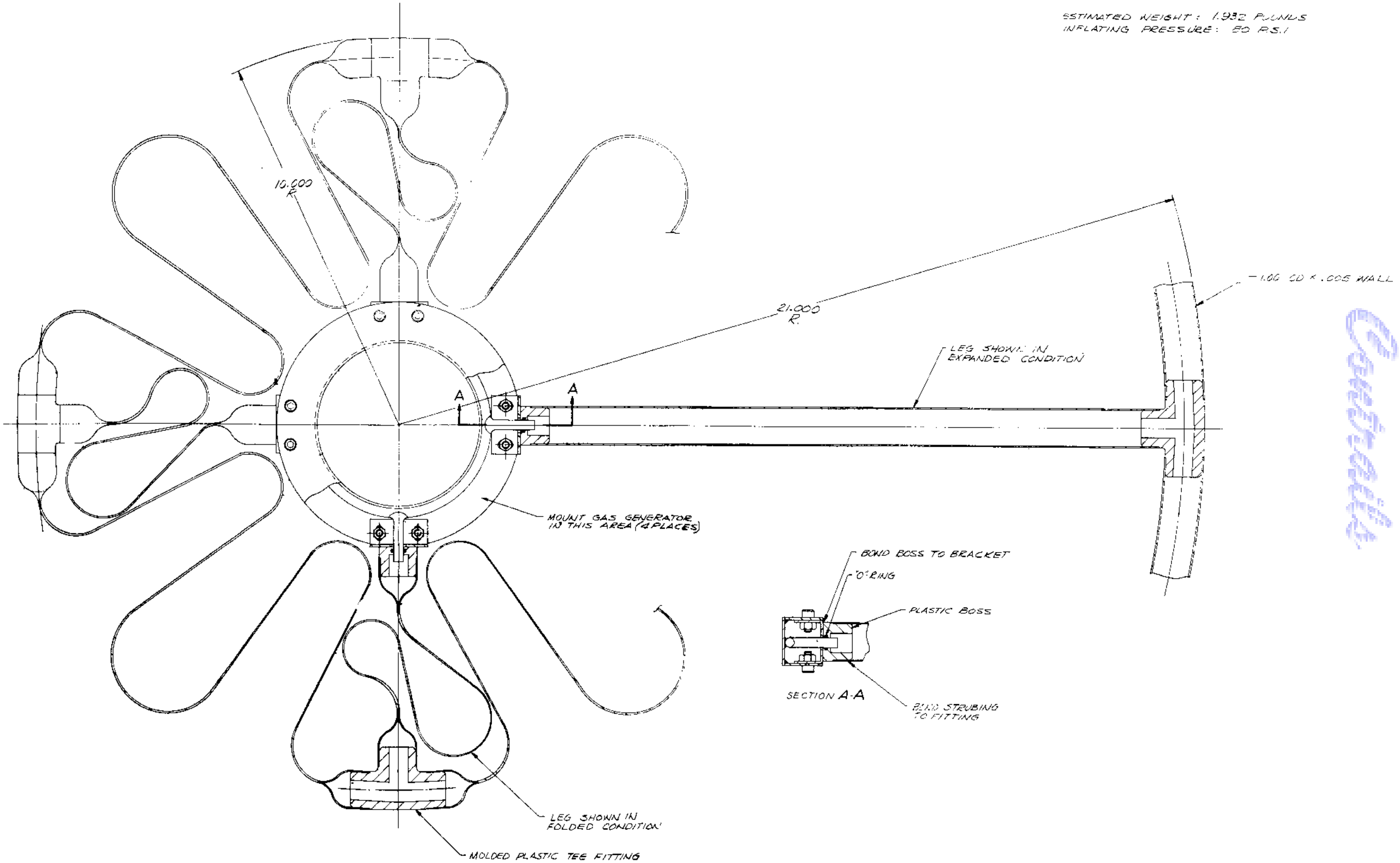
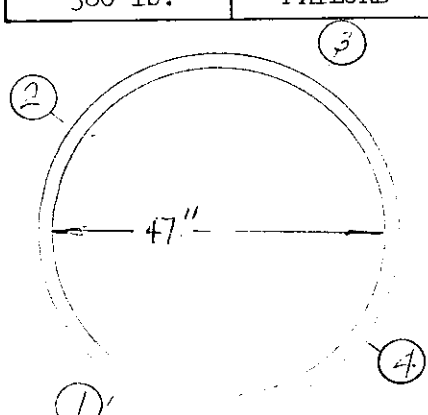


FIGURE 16 EXPANDABLE TOROIDAL FRAME

TABLE VIII

TORUS TRUSS DATA

LOAD	GUAGE 1	GUAGE 2	GUAGE 3	GUAGE 4
4 lb. 1 oz.	0	0	0	0
40 lb.	+.006	+.002	+0	+.0012
60 lb.	+.009	+.0032	+.001	+.0037
80 lb.	+.0108	+.0031	+.0011	+.0037
100 lb.	+.0147	+.0040	+.0039	+.006
120 lb.	+.014	+.0041	+.0025	+.0071
140 lb.	+.0134	+.0042	-.0005	+.0075
160 lb.	+.0145	+.0049	-.0015	+.0075
180 lb.	+.0137	+.005	-.0028	+.0079
200 lb.	---	---	---	---
220 lb.	+.0169	+.0061	-.0049	+.006
240 lb.	+.0169	+.0068	-.0062	+.0062
260 lb.	+.017	+.0078	-.0078	+.0072
280 lb.	+.0179	+.0081	-.009	+.0074
300 lb.	+.0189	+.0184	-.0207	+.0201
320 lb.	+.024	+.0176	-.0219	+.020
340 lb.	+.0258	+.0163	-.022	+.0215
360 lb.	FAILURE			



7/8" I.D. x .005" Wall Thickness

Failed at #1 Guage where there were several local buckles initially and where pressure line was connected.

Minus readings indicate change in direction of guage travel.

The strain resulting from these stresses accomplishes the proportional stretching required for a toroid. After annealing to remove work hardening, the tube can be reflattened and folded in any geometry; it will always inflate into a circular configuration. Figure 15 shows the setup to test this torus for a uniformly distributed radial load. Table VIII shows the load increment and deflections at four diametrically opposite points. Failure load was 360 lbs. Total weight of toroid was 0.203 lbs. A direct application of this principle was provided by a design problem dealing with precision decoys. It was required to provide radial support to a fabric shell of a given diameter. The support had to be concentric with the ℄ of thrust within close limits. Figure 16 on page 29 shows how this was done with the help of four radial arms and a toroidal structure.

Our plastic division is presently tackling the problem of foaming in vacuum. There is little doubt in our minds that foam filled aluminum shells would generate a new family of structures with an exceptionally high strength/weight ratio.

CONCLUSION

Our investigation has proved that foldable structures of appreciable strength and rigidity can be achieved with a metallic foil, aluminum for example.

Though considerable analytical work remains to be done and manufacturing processes must be streamlined. The results obtained so far from the efforts of a few people gives ample justification for further experimentation.

REFERENCES

Page 10, 11, 12 are extracted from: "RAD-TM-61-4" Collapse of Erectable Al Foil Tubes Under Axial Compression by Victor W. Miselis.